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14. ABSTRACT

We have developed methods based upon soliton perturbation theory and importance sampling to simulate rare events in lightwave systems, including mode-locked laser systems. A key step to using the methods based upon soliton perturbation theory is to use an approximate version of the system dynamics to determine the locations in the large-dimensional state space that most contribute to the desired rare events (e.g., errors). In this method, calculus of variations applied to the approximate system allows the most significant rare events to be located, and then fully-detailed importance-sampled Monte-Carlo simulations in the vicinity of these locations properly determines the probabilities of these rare events and corrects for any errors made by the approximations in determining the system dynamics. In the case of the simulations of mode-locked lasers, the analysis shows that the system dynamics are related to the classical exit-time problem of stochastic differential equations.

15. SUBJECT TERMS

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Simulation Methods for Rare Events in Nonlinear Lightwave Systems
AFOSR Grant FA9550-04-1-0289

Final Progress Report
1 June 2004 - 30 August 2007

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OBJECTIVES

The objectives of this project were to develop new hybrid analytical/computational methods that are capable of simulating the rare events that are the determining factors of the performance of lightwave systems and devices. These methods use: 1) Analytical techniques, such as perturbation and asymptotic methods, to guide numerical simulations using importance sampling; 2) Adaptive numerical methods, such as the multicanonical Monte Carlo and cross-entropy methods, to perform the simulation of rare events when guiding analytical models are not available. The above methods can be used to evaluate the performance of specific optical systems and devices, including ultra-high-precision optical clocks based upon mode-locked fiber lasers; optical clocks and other devices based upon hybrid opto-electronic oscillators. In each case, the goal is to use the methods to develop models that can accurately predict the performance of these devices, as well as determine the failure modes that are the limiting factors in their performance.

STATUS OF EFFORT

Importance sampling has been applied to compute the performance of a differential-phase-shift keyed (DPSK) system. The results of basic method were published in Photonics Technology Letters, and more detailed publications explaining the methods have been published in the Society for Industrial and Applied Mathematics (SIAM) Journal on Applied Mathematics, and submitted to the SIAM Journal on Applied Dynamical Systems. The method has been optimized, and a numerical implementation ported to run on a 64-processor Beowulf cluster. This implementation was used to determine the optimal placement of an in-line phase-conjugator (the conjugator improves system performance by reducing phase noise). This work was presented at the Conference on Lasers and Electrooptics in Baltimore, Maryland. We next applied the importance-sampling method to the simulation of a mode-locked laser. The method allows amplitude drop-outs and position shifts to be efficiently simulated in these systems. This work was reported at the 2007 Conference on Lasers and Electro-Optics, held in Baltimore, Maryland. Finally, a new iterative numerical method employing the singular value decomposition and based on the cross-entropy method has been developed.

ACCOMPLISHMENTS/NEW FINDINGS

We have developed methods based upon soliton perturbation theory and importance sampling to simulate rare events in lightwave systems, including mode-locked laser systems. A key step to using the methods based upon soliton perturbation theory is to use an approximate version of the system dynamics to determine the locations in the large-dimensional state space that most contribute to the desired rare events (e.g., errors). In this method, calculus of variations applied to the approximate system allows the most significant rare events to be located, and then fully-detailed importance-sampled Monte-Carlo simulations in the vicinity of these locations properly determines the probabilities of these rare events and corrects for any errors made by the approximations in determining the system dynamics. In the case of the simulations of mode-locked lasers, the analysis shows that the system dynamics are related to the classical exit-time problem of stochastic differential equations. For example, if a periodic signal is added to control the pulse position, pulses tend to locate themselves at the bottom of an effective potential well created by the periodic signal, and noise causes the pulses to, once in a great while, to climb up the potential well and escape into a neighboring potential well. If the noise is weak the probability of these rare events is very small.

More recently we have developed a new fully-numerical method based upon the singular value decomposition and the cross-entropy method. The singular value decomposition is applied to the equations linearized about a specific nonlinear solution and allows one to determine numerically the specific perturbations that produce the largest change in some desired output quantity or performance measure, and thus replaces the step of determining the approximate dynamics using soliton perturbation theory. Because it is fully numerical, non-soliton pulses can be examined. Next, the most probable perturbations are computed using the cross-entropy method. This method uses the Kullback-Liebler probability distance measure to compute the deviation between the current Monte-Carlo sampling distribution and the optimal importance-sampling biasing distribution. By iterating to decrease the difference between the current and the optimal distribution (which can't be computed directly itself), one can reach the most probable locations in state space that produce errors. Because the techniques used in this method are very general, we anticipate that it can be used to explore nonlinear systems for which rare events are significant other than lightwave systems.

PERSONNEL SUPPORTED

* Faculty

William L. Kath, Northwestern University

* Graduate Students

Elaine T. Spiller
Graham M. Donovan

PUBLICATIONS

Refereed:

* Journals

E. T. Spiller, W. L. Kath, R. O Moore and C. J. McKinstrie, Computing large signal distortions and bit-error ratios in DPSK transmission systems, Photonics Technology Letters, vol 17, no. 5, May 2005, pages 1022-1024.

R. O. Moore, G. Biondini and W. L. Kath, A method to compute statistics of large, noise-induced perturbations of nonlinear Schroedinger solitons, SIAM J. Applied Math, vol 67, no. 5, July 2007, pages 1418-1439.

Submitted:

E. T. Spiller and W. L. Kath, A method for determining most-probable errors in nonlinear lightwave systems, submitted to the SIAM Journal on Applied Dynamical Systems.

* Conferences

Refereed:

E. T. Spiller, G. M. Donovan and W. L. Kath, Direct determination of range extension due to phase conjugation in a soliton-based DPSK transmission system, Conference on Lasers and Electro-optics 2005 Technical Digest, CWO4.

G. M. Donovan, E. T. Spiller and W. L. Kath, Non-Gaussian optical field statistics in a long-haul soliton-based DPSK transmission system, Conference on Lasers and Electro-optics 2005 Technical Digest, JThE76.

G. M. Donovan and W. L. Kath, Rare Event Simulation of the Performance of an Actively Mode-Locked Fiber Laser Model, Conference on Lasers and Electro-optics 2007 Technical Digest, JThA87.

INTERACTIONS/TRANSITIONS

* Participation/Presentations At Meetings, Conferences, Seminars, Etc

G. M. Donovan and W. L. Kath, Rare Event Simulation of the Performance of an Actively Mode-Locked Fiber Laser Model, Conference on Lasers and Electro-optics, Baltimore, MD, May 2007.

W. L. Kath, Methods for simulating rare events in soliton-based lightwave systems, Department of Applied Mathematics, University of Colorado, Boulder, April 2007.

W. L. Kath, Methods for simulating rare events in soliton-based lightwave systems, Department of Mathematics, Illinois Institute of Technology, Chicago, Illinois, February 2007.

W. L. Kath, Methods for simulating the effects of noise in soliton-based lightwave systems, Society for Industrial and Applied Mathematics Conference on Nonlinear Waves and Coherent Structures, Seattle, WA, September 2006.

W. L. Kath, Methods for simulating the effects of noise in soliton-based lightwave systems, Joint UBC SCAIM/SFU CSC Seminar, Simon Fraser University, Vancouver, BC, Canada, September 2006.

W. L. Kath, Simulating the Effects of Noise in Soliton-based Communication Systems, Center for Applied Mathematics Spring Workshop in Stochastic Modeling, University of Notre Dame, March 2006

W. L. Kath, Low-probability events in an actively mode-locked laser model," Transformational Communications Advanced Technology Study Review Meeting, Arizona Center for Mathematical Sciences, University of Arizona, Tucson, AZ, May 2006.

W. L. Kath, Importance sampling for soliton-based lightwave systems, Workshop on Nonlinearity and Randomness in Complex Systems, University of Buffalo, Buffalo, NY, March 2006.

W. L. Kath, Simulating the effects of noise in soliton-based communication systems, International Conference on Stochastic Analysis and Partial Differential Equations, Northwestern University, June 2006.

W. L. Kath, Simulating the effects of noise in soliton-based communication systems, International Conference on Nonlinear Waves, Integrable Systems and Applications, University of Colorado, June 2006.

W. L. Kath, Methods for simulating rare events in optical systems, VISSTA'05 Workshop, North Carolina State University, May 2005.

W. L. Kath, Simulating rare events in lightwave systems with importance sampling (plenary talk), Foundations of Applied and Computational Mathematics, New Jersey Institute of Technology, May 2005.

E. T. Spiller, G. M. Donovan and W. L. Kath, Direct Determination of Range Extension Due to Phase Conjugation in a Soliton-Based DPSK Transmission System, OSA Conference on Lasers and Electro-optics, May 2005

G. M. Donovan, E. T. Spiller and W. L. Kath, Non-Gaussian Optical Field Statistics in a Long-Haul Soliton-Based DPSK Transmission System, OSA Conference on Lasers and Electro-optics, May 2005.

E. T. Spiller, G. M. Donovan and W. L. Kath, Modeling and computation of error rates in lightwave systems due to nonlinear phase noise, IMACS Conference on Nonlinear Evolution Equations and Wave Phenomena: Computation and Theory, Athens, GA, April 2005.

W. L. Kath, Extracting solitons out of noise, IMACS Conference on Nonlinear Evolution Equations and Wave Phenomena: Computation and Theory, Athens, GA, April 2005.

W. L. Kath, Phase noise in soliton-based differential phase-shift-keyed systems, Society for Industrial and Applied Mathematics Conference on Nonlinear Waves and Coherent Structures, Orlando, Florida, October 2004.

W. L. Kath, Methods for the simulation of rare events in lightwave systems," Workshop on Mathematical Ideas in Nonlinear Optics: Guided Waves in Inhomogenous Nonlinear Media, International Center for the Mathematical Sciences, University of Edinburgh, July 2004.

NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES

HONORS/AWARDS

W. L. Kath, Elected Fellow of the Optical Society of America, Fall 2006